

Ionization freeze-out and barium problem in supernova 1987A

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Abstract

We have shown that in the atmosphere of SN 1987A level populations of hydrogen are mostly controlled by an ionization freeze-out and ion-molecular processes up to ~ 40 days. The ionization freeze-out effects are important for normal SNe II-P as well. The time dependent effects and the mutual neutralization between H^- and H^+ may result in a non-monotonic radial dependence of the Sobolev optical depth for $H\alpha$ and then in a blue emission satellite of $H\alpha$ observed in SN 1987A spectra at Bochum event phase. The relative abundance of molecular hydrogen $n(H_2)/n(H) \sim 10^{-4}-10^{-3}$ is high enough for the photospheric phase of SN 1987A. We emphasize that the poor knowledge of the far UV radiation field in the envelope of SN 1987A still forbids a truly reliable estimate of the Ba abundance but well-constructed and tested models may improve this situation.

1.1 Introduction

As time goes on an impression strengthens that almost everything is well understood with respect to supernova (SN) 1987A in the Large Magellanic Cloud (LMC). But it is not the case. Let us consider merely two neighbor lines: $H\alpha$ and Ba II 6142 Å. At early times (during 20–100 days) the $H\alpha$ line exhibits a striking fine structure called "Bochum event" [1]. This phenomenon was originally described as two additional emission-like features, a red emission satellite (RES) and a blue emission satellite (BES). Such an $H\alpha$ profile was supposed to result from a superposition of an asymmetric and a spherically symmetric component [2].

The asymmetric component responsible for the RES detail consisted of the bright core with the radial velocity of $+4000 \text{ km s}^{-1}$ and the extended halo of a lower brightness. A transversal velocity of the core of 2400 km s^{-1} , estimated with the effect of the occultation of the asymmetric component by the photosphere, together with the radial velocity gave the absolute velocity of 4700 km s^{-1} . It was evident that the core of the asymmetric component coincided with the ^{56}Ni clump, which should have the same absolute velocity of 4700 km s^{-1} . The amount of ^{56}Ni in the fast clump was estimated as $\sim 10^{-3} M_{\odot}$. The symmetric component was adapted to match the BES feature of $H\alpha$ and was characterized by the non-monotonic radial dependence of the Sobolev optical depth which had no physical explanation.

The unusually strong Ba II 6142 Å line in early spectra of SN 1987A is a distinctive feature of this supernova [3], which still remains a subject of great concern after first studies [4, 5] claimed the large (up to a factor of 20) Ba overabundance derived from the line strength. The problem is that the s -process nucleosynthesis in massive stars evolving to the presupernova star of SN 1987A [6] is not able to yield the Ba overabundance in the hydrogen envelope by

more than a factor of 1.4 assuming that a total ejecta mass is $15 M_{\odot}$, a mass-cut is at $2 M_{\odot}$ [7], and the synthesized Ba is completely mixed over the ejecta.

More naturally is to consider the large strength of Ba II 6142 Å as the outcome of specific conditions in the SN 1987A atmosphere. It was recognized that if Ba in the envelope of SN 1987A was mostly in Ba II ion form then the Ba II 6142 Å line might be reproduced with the Ba abundance typical for the LMC [8]. The absence of strong Ba lines in normal SNe II-P was explained then by the fact that Ba in the atmosphere of these supernovae was mostly in Ba III form. An atmosphere model based on solving the radiation transfer equation with the Monte Carlo technique was able to account for the low strength of Ba II lines in normal SNe II-P for the solar abundance, but failed to produce strong Ba II lines in SN 1987A for the LMC abundance [9]. It was acknowledged that this atmosphere model of SN 1987A used for Ba II lines simulation was presumably not adequate enough because of a poor agreement in hydrogen Balmer line intensities.

Generally, until recently the modelling of hydrogen lines in SN 1987A at the photospheric epoch has remained a challenging problem for spectrum synthesis (e.g. [10]). Situation has changed recently, when it has become clear that the major drawback of standard atmosphere models for SNe II-P was an assumption of the statistical equilibrium. It has been shown in the frame of time dependent chemical kinetics that an ionization freeze-out plays a crucial role in the ionization and excitation of hydrogen in the atmosphere of SNe II-P at the photospheric epoch [11, 12]. Moreover, in the atmosphere of SN 1987A ion-molecular processes might become essential in producing ionization of hydrogen. In view of these results a motivation of the work is to take time dependent effects into account, to construct an adequate model, to succeed in reproducing H α profile, and then to study the Ba II 6142 Å line in SN 1987A at the photospheric epoch.

Model and Input Physics

A full model should be based on the hydrodynamic model and time-dependent radiation transport, and should include self-consistent electron temperature evolution and full reaction network.

Our present model is based on the hydrodynamic model [13] which has an ejecta of mass $15 M_{\odot}$ and a kinetic energy of 1.44×10^{51} erg. The radiation field is treated in the approximation of clear-cut photosphere and above atmosphere. For $t < 1.8$ days the radiation field in continuum is described by the photospheric radius and effective temperature, taken from the hydrodynamic model, and then by those observed [14] and by the approximated UV and optical observations [15]. The line radiation transfer is treated in the modified Sobolev approximation [16, 17] as a purely local process. Instead of solving the energy equation we use two regimes for the electron temperature: radiative equilibrium and adiabatic approximation.

The following elements and molecules are calculated in non-LTE chemical kinetics: H, He, C, N, O, Ne, Na, Mg, Si, S, Ar, Ca, Fe, Ba, H $^{-}$, H $_2$, H $_2^{+}$, and H $_3^{+}$. All elements but H are treated with the three ionization stages. The level populations of H and Ba II are calculated for 15 and 17 levels, respectively, and the rest of atoms and ions are assumed to consist of the ground state and continuum. The reaction network involves all bound-bound and bound-free, radiative and collisional processes for atoms and ions, and 7 radiative and 37 collisional processes for molecules. To reproduce the chemical composition typical to the LMC situation [18] all metal abundances are scaled to $1/2.88$ their solar values.

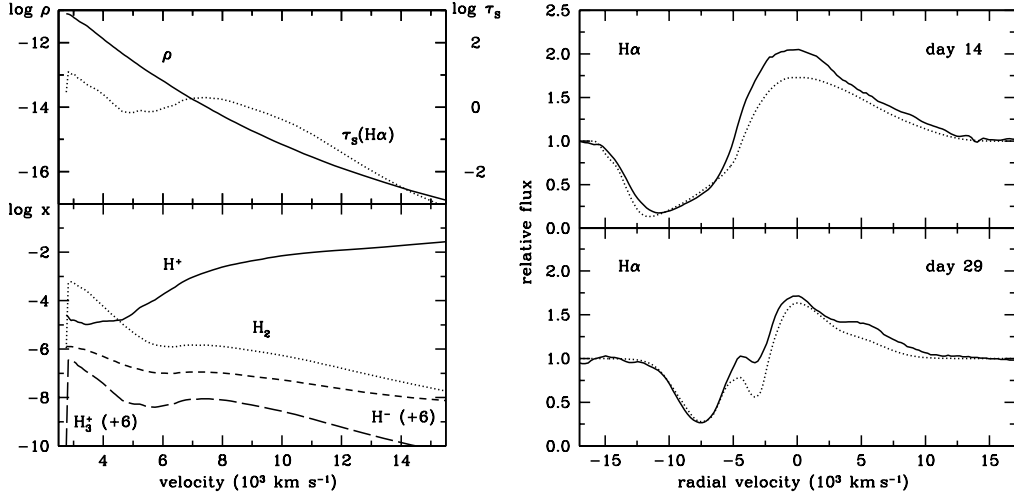


Figure 1: Upper left panel: Density (solid line) and the Sobolev optical depth of H α (dotted line) as a function of velocity for day 29. Lower left panel: Velocity dependence of the following fractional abundances for day 29: $x(\text{H}^+)$ (solid line), $x(\text{H}_2)$ (dotted line), $x(\text{H}^-)$ (short dashed line), and $x(\text{H}_3^+)$ (long dashed line). Dashed lines are shifted by a +6 order of magnitude. Right panel: Observed (solid line) and calculated (dotted line) H α profile for days 14 and 29.

Results

We have developed a time dependent chemistry model for supernova envelope at photospheric phase and investigated spectra of SN 1987A. On day 29 Fig. 1 shows the specific non-monotonic radial dependence of the Sobolev optical depth of H α over envelope with minimum near the photosphere. Just such a distribution we need to reproduce the BES feature of H α profile. Note that the fractional abundance of molecular hydrogen of the order of 10^{-4} is high enough for the photospheric phase of SN 1987A. The fit between the observed and calculated H α profiles on days 14 and 29 is fairly good in Fig. 1 indicating that we have constructed a correct model.

The influence of time dependent effects on the H α profile is shown in Fig. 2. It is clear that the ionization freeze-out plays a key role in producing the ionization and excitation of hydrogen for times nearly up to day 40 when the non-thermal ionization and excitation resulting from radioactive ^{56}Ni decays become essential [13]. In addition, from Fig. 2 it is evident that molecules are mainly responsible for the formation of the minimum of the Sobolev optical depth above the photosphere and, as a consequence, for the BES feature at Bochum event phase. A leading reaction in the neutralization of ionized hydrogen is mutual neutralization between H^- and H^+ : $\text{H}^- + \text{H}^+ \rightarrow 2 \text{H}$.

Now when we have got a confidence in reproducing the observed H α profile we can study the barium line. In Fig. 3 there is a good fit between the observed and calculated Ba II 6142 Å line but the approximated UV and optical observations result in the Ba overabundance ratio ≈ 12 for the time-dependent solution and ≈ 16 for the steady one. The point is that the fractional abundance of Ba II in the supernova envelope turns out too low to produce the strong barium line with the low Ba overabundance ratio. We have analyzed this situation and

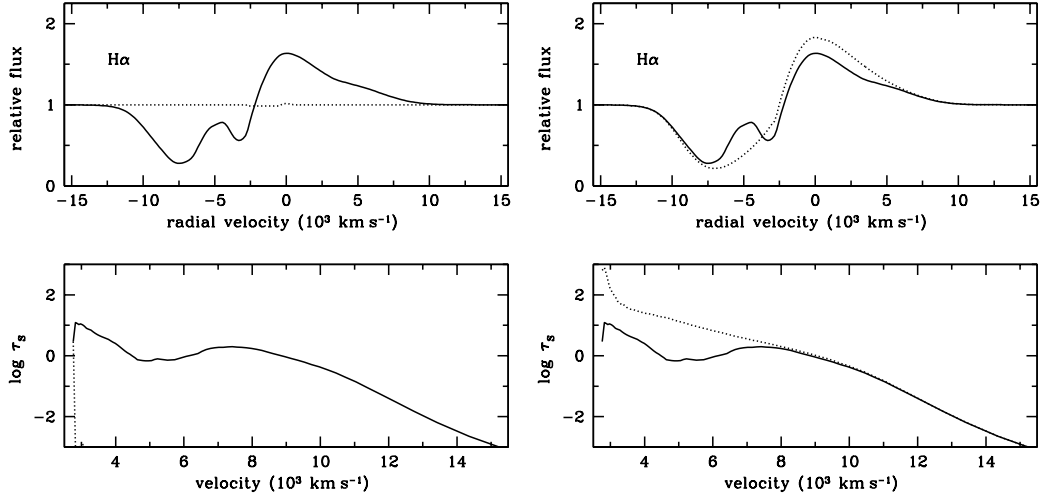


Figure 2: Calculated $H\alpha$ profile and the Sobolev optical depth as a function of velocity for day 29. Influence of non-stationarity (left panel) and molecules (right panel) is shown by dotted line.

found out that, it is evident, the fractional abundance of Ba II is very sensitive to the radiation flux at photon energies responsible for Ba II ionization from ground state and excited levels.

Discussion

To evaluate the influence of the radiation flux on the Ba II fractional abundance we calculate a toy model with the Ba abundance ratio of 1.4 as predicted from the s -process nucleosynthesis. In this model the calculated Ba II 6142 Å line matches the observed one as shown in Fig. 3 assuming a reduction of the radiation flux by a factor of ≈ 17 in the far UV region.

So, the far UV radiation field plays a vital role in estimating Ba abundance in SN 1987A. A crucial question is whether the observed flux is an intrinsic flux of SN 1987A or not. Taking a number of uncertainties in measuring the far UV flux of SN 1987A into account it is reasonable to assume that the observed flux is presumably not related to the radiation field in the region where the barium line forms. Thus we have at least two alternatives: pessimistic and optimistic. If we consider the observed flux as responsible for the Ba II ionization in supernova envelope we should accept the Ba abundance as large as 12 or so. And there is nothing more to do. This is the pessimistic alternative. In opposite case we can solve the radiation transfer equation in far UV region, check the solution in some way, and estimate Ba abundance in SN 1987A. It is the optimistic alternative.

Conclusions

We have developed a time dependent chemistry model for supernova envelope at photospheric phase that, in connection with hydrodynamic models, provides a powerful tool to investigate supernova spectra.

We have shown that level populations of hydrogen are mostly controlled by an ionization freeze-out and ion-molecular processes up to ~ 40 days in the atmosphere of SN 1987A. The

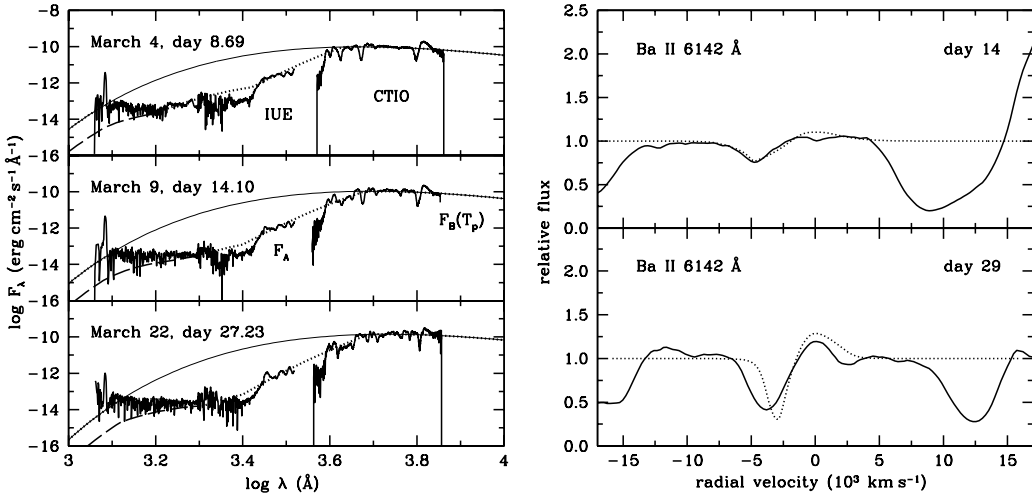


Figure 3: Left panel: The combined UV (IUE) and optical (CTIO) spectra of SN 1987A [15] (thick solid line), the black-body flux at the effective temperature (thin solid line), the approximated emergent flux (dotted line), and the approximated emergent flux reduced by a factor of ≈ 17 at $\log \lambda < 3.2 - 3.3$ (long dashed line) for days 8, 14, and 27. Right panel: Observed (solid line) and calculated (dotted line) Ba II 6142 Å line for days 14 and 29.

ionization freeze-out effects are important for normal SNe II-P as well.

The time dependent effects and mutual neutralization between H^- and H^+ may result in a non-monotonic radial dependence of the Sobolev optical depth for $H\alpha$ and then in a blue emission satellite of $H\alpha$ observed in SN 1987A spectra at Bochum event phase.

It should be noted that the relative abundance of molecular hydrogen $n(H_2)/n(H) \sim 10^{-4} - 10^{-3}$ is high enough for the photospheric phase of SN 1987A.

We emphasize that the poor knowledge of the far UV radiation field in the envelope of SN 1987A still forbids a truly reliable estimate of the Ba abundance but well-constructed and tested models may improve this situation.

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